STAFF SUMMARY SHEET

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SUMMARY

1. PURPOSE. To provide security and policy review on the document at Tab 1 prior to release to the public.

2. BACKGROUND.
Authors: Jerry Sell (DFP-LORC, 333-0989), Alina Gearba (University of Southern Mississippi), Randall Knize (DFP, 333-4165)

Title: Blue and Infrared Coherent Beams Generated by Multiple Wave Mixing in Rb Vapor

Document type: Journal Article

Description: This article presents our recent work producing low power coherent beams using nonlinear optical effects in rubidium vapor. Using multiple wave mixing we are able to convert near infrared laser light to different wavelengths in the blue and IR spectrum.

Release Information: The paper will be submitted to the journal Optics Letters

Previous Clearance information: None

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3. DISCUSSION. This work is supported by the Air Force Office of Scientific Research and the National Science Foundation.

4. VIEWS OF OTHERS. N/A

5. RECOMMENDATION. Sign coord block above indicating document is suitable for public release. Suitability is based solely on the document being unclassified, not jeopardizing DoD interests, and accurately portraying official policy.

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CORY T. LANE, Maj, USAF
Director of Research
Department of Physics

Tab
1. Journal Article

Blue and Infrared Coherent Beams Generated by Multiple Wave Mixing in Rb Vapor

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Utilizing nonlinear optical processes in Rb vapor we observe the generation of coherent optical fields at 420 nm and 1324 nm. Input laser beams at 780 nm and 776 nm enter a heated Rb vapor cell collinear and circularly polarized. Rubidium atoms are excited to the $5D_{5/2}$ state, with cascading decays through the $6P_{3/2} \rightarrow 5S_{1/2}$ and $6S_{1/2} \rightarrow 5P_{1/2}$ states producing blue (420 nm) and IR (1324 nm) beams, respectively. Scaling the input 780 nm and 776 nm laser powers to greater than 200 mW we obtain a coherent blue beam of 9 mW power, almost an order of magnitude larger than previously achieved, while also producing an IR beam of up to 2.5 mW power. We describe the dependences of both beams in relation to the Rb density, the frequency detuning between Rb ground state hyperfine levels, and the input laser intensities.

OCIS codes: 190.4223, 270.1670, 190.7220.

A wide range of interesting phenomena can be created by utilizing nonlinear optical processes in a dense atomic vapor. Large enhancements of these processes is possible through the generation of quantum coherences among atomic states and include effects such as electromagnetically induced transparency [1], fast and slow light propagation [2], four-wave mixing [3], and lasing without inversion [4]. Four-wave mixing (FWM) in particular has been shown to produce both efficient frequency up-conversion [5–7] and down-conversion [8] using low power continuous wave (cw) lasers. The created optical fields are narrowband tunable coherent light sources, with wavelengths from the IR to approaching the UV depending upon the atomic states involved.

Frequency up-conversion by FWM has most often been studied in Rb vapor, first demonstrated using low power cw lasers by Zibrov *et al.* in 2002 [5] where 15 μW of coherent radiation at 420 nm was achieved. The method relies upon input lasers at 780 nm and 776 nm [see Fig. 1(a)] driving atoms on the dipole-forbidden $5S_{1/2} \rightarrow 5D_{5/2}$ transition, using the $5P_{3/2}$ level as an intermediate state. Aided by the long lifetime of the $5D_{5/2}$ level (240 ns), a population inversion between the $5D_{5/2} \rightarrow 6P_{3/2}$ level occurs, producing a third optical field by amplified spontaneous emission at 5.23 μm. Strong atomic coherences are thus formed in a diamond-type energy level structure, creating coherent blue light at 420 nm ($6P_{3/2} \rightarrow 5S_{1/2}$) by FWM. Recent experiments achieved first 40 μW of 420 nm light through the additional coupling of both $5S_{1/2}$ hyperfine ground state levels [9], and subsequently 1.1 mW by further optimization of input laser polarizations and frequencies [7]. Utilizing corresponding atomic states in Cs, 4 μW of coherent blue light was generated at 455 nm [10], illustrating the application of this method to less ideal atomic states as only 0.4% of Cs atoms cascade from $6D_{5/2} \rightarrow 7P_{3/2}$ compared to 35% of Rb $5D_{5/2}$ atoms which decay through the $6P_{3/2}$ state [11].

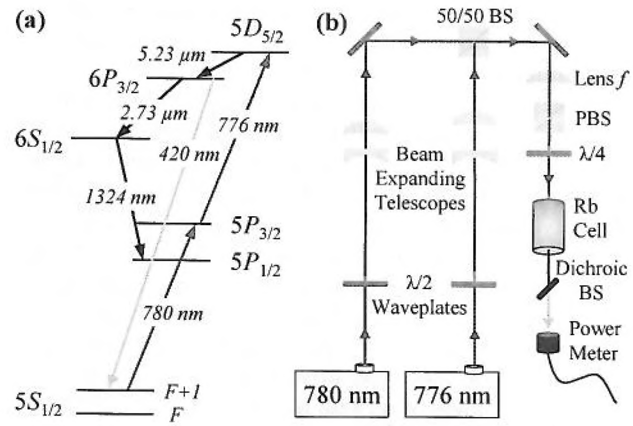

Fig. 1. (Color online) (a) Relevant Rb energy levels. Excitation lasers (cw) are present at 780 nm and 776 nm while coherent output beams are observed at 420 nm and 1324 nm. (b) Schematic of the experimental setup.

In this Letter we demonstrate both frequency up-conversion to 420 nm and down-conversion to 1324 nm using multiple wave mixing in Rb vapor. Substantially greater coherent blue beams ($\geq$ 9 mW) are achieved by scaling the 776 nm and 780 nm input powers while adjusting their frequency detunings along with the Rb density in order to obtain optimal phase matching and optical depths for blue beam generation and transmission. The coherent and collimated blue light can be used as a basis for applications such as sensitive atom detection [12], quantum information processing [13], and underwater communication [14]. The simultaneously gener-

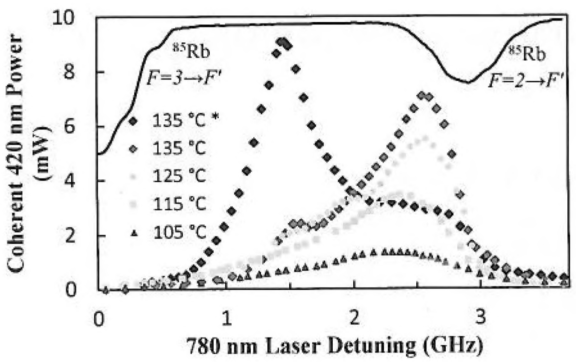

Fig. 2. (Color online) Dependence of the generated blue beam power on the frequency detuning of the 780 nm input laser (the 776 nm frequency is always correspondingly tuned to remain on the $5D_{5/2}$ resonance). * denotes laser beam diameters of roughly twice the other data sets.

ated 1324 nm beam has not been studied before in detail; however, we observe excellent spatial coherence and up to 2.5 mW powers, producing a novel light source at a telecommunication wavelength.

The experimental setup is illustrated schematically in Fig. 1(b). A master oscillator power amplifier system (Sacher Lasertechnik) drives the D_2 transition in Rb at 780 nm, while a titanium:sapphire laser (Coherent MBR-110) drives the $5P_{3/2} \rightarrow 5D_{5/2}$ transition at 776 nm. The two laser beams are combined in a 50/50 non-polarizing beamsplitter and pass through a $\lambda/4$ waveplate in order to achieve co-propagating and circularly polarized input optical fields, whose importance in coherent blue light generation has been identified in previous experiments [7,9]. Unless otherwise noted, an $f = 250$ mm lens is used to focus the laser beams to a waist radius of $\simeq$ 100 μm in the vapor cell, resulting in intensities of up to 10^3 W/cm^2 (350 mW power) in each laser beam, along with a depth of focus approximately the length of the vapor cell (5 cm). The Rb vapor cell contains a natural abundance of Rb and is operated from $105 - 135$°C ($8\times10^{12}-5\times10^{13}$ cm^{-3}). Beam expanding telescopes are also incorporated into each laser beam path to optimally overlap the beams in the Rb vapor cell, particularly important at high Rb densities where a significant optical Kerr effect can occur.

The 780 nm frequency is defined in relation to its detuning from the ^{85}Rb $5S_{1/2} : F = 3 \rightarrow 5P_{3/2} : F'$ absorption peak in a room temperature vapor cell. Figure 2 shows the coherent 420 nm power generated as a function of this detuning (δ_{780}), where the 776 nm laser detuning (δ_{776}) is correspondingly adjusted to remain on the $5D_{5/2}$ resonance, $\delta_{780} = -\delta_{776}$. A steady rise in the generated blue beam power is observed with increasing Rb density, as long as increasing input powers are available (see Fig. 3). A maximum blue beam power of 9.1 mW is achieved by adjusting the input beams waist radii ($\simeq$ 200 μm) along with the frequency detunings, using input powers of $P_{780} = 390$ mW and $P_{776} = 205$ mW.

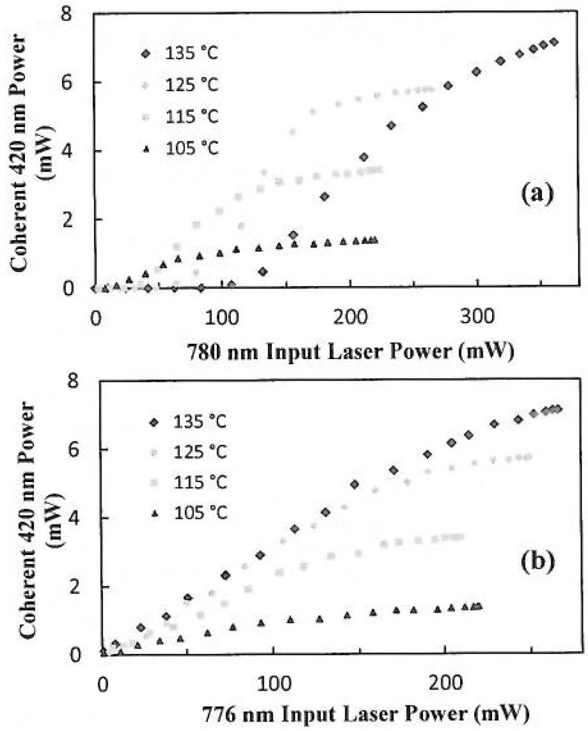

Fig. 3. (Color online) (a) Output blue (420 nm) power measured for an input 776 nm power $\geq$ 200 mW and varying 780 nm input powers. (b) Blue power measured with an input 780 nm laser power $\geq$ 200 mW and varying 776 nm input powers.

These results can be qualitatively understood by considering the phase matching conditions $\vec{k}_{780} + \vec{k}_{776} = \vec{k}_{420} + \vec{k}_{5230}$ for this FWM process, with the wave vectors $k_\omega = \omega/c \cdot n_\omega$, where n is the refractive index at the respective frequency. The 780 nm and 420 nm optical fields encounter the largest refractive index variation as they are readily absorbed in the dense Rb vapor. Studies by Meijer *et al.* [6] at low powers determined the smallest changes in these refractive indexes for 780 nm detunings from $1 - 3$ GHz. This agrees with our data at $\geq$ 10 times the input laser intensities, with small changes in the laser detuning necessary as the Rb density and laser intensity are increased, and a large change in detuning occurring when the laser intensities are dramatically changed through larger focused beams. This also agrees with other low power studies which determined optimum blue powers for 780 nm detunings directly between the ^{85}Rb ground hyperfine states [7,9].

Figure 3 illustrates the generated blue beam power as a function of each input beam power for vapor cell temperatures from $105 - 135$°C. As the 780 nm input power is increased [Fig 3(a)], we observe both a threshold-like behavior along with saturation of the blue beam power. These characteristics can be described by considering

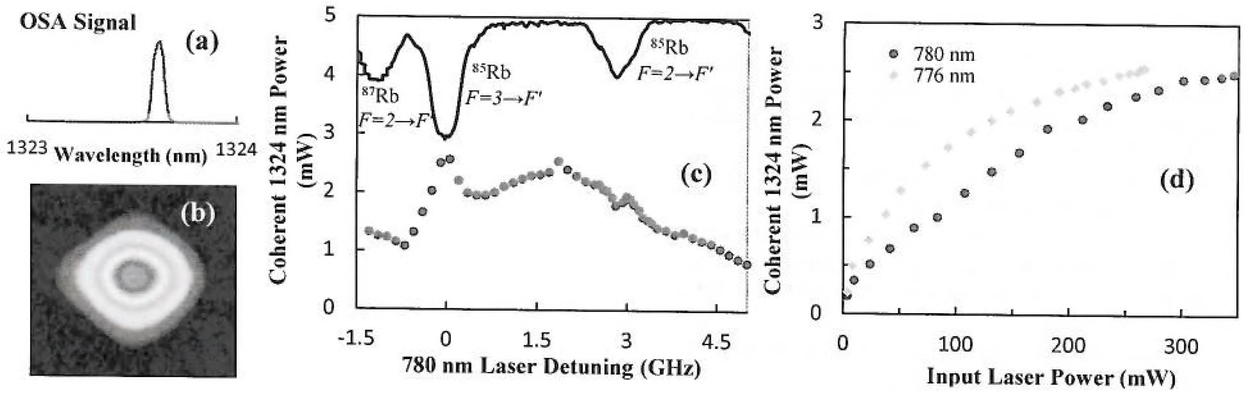

Fig. 4. (Color online) (a) OSA spectra of the IR beam. (b) IR beam spatial profile. (c) Generated IR beam power as input lasers are scanned in frequency. (d) IR power dependence on input laser power (as one input beam power is increased the other is held constant at its maximum power).

the optical depths (OD) for the 780 nm and 420 nm beams. The optical depth, $\mathrm{OD} = N\sigma l$, where N is the Rb density, σ is the absorption cross section, and l is the length of the vapor cell. In our case σ must take into account the off resonant excitation, Doppler broadening, the laser intensity along with the frequency dependent saturation intensity. At the level where the blue power saturates with increasing 780 nm input power we find an approximately constant optical depth over the range of Rb densities examined. At low 780 nm powers and for our detunings the optical depth becomes too large and the 780 nm beam is quickly absorbed in the initial length of the vapor cell, along with the generated blue beam. Figure 3(b) does not show these characteristics as the 780 nm beam is already at saturation intensities, allowing the generated blue beam to escape the Rb vapor even at low 776 nm intensities as ground state absorption is greatly reduced.

During analysis of the generated blue beam, we also observed an IR beam at 1324 nm [Fig. 4(a)], measured using an Anritsu MS9710 optical spectrum analyzer (OSA). Figure 4(b) illustrates the primarily single-mode spatial profile of this beam. We have not found previous observations of such a cw beam; however, Zibrov *et al.* [5] did measure a 1.3 μm beam which they accounted for by FWM through $6S_{1/2} \rightarrow 5P_{3/2}$ (1.36 μm). Scanning laser frequency detunings over a large range [Fig. 4(c)], we only observed a unidirectional 1324 nm beam which we attribute to six-wave mixing through the $6S_{1/2} \rightarrow 5P_{1/2}$ states. The different phase matching requirements allows the generation of this beam over a much broader detuning range than the blue beam. The absence of $5P_{1/2}$ excitation results in a negligible optical depth and significant 1324 nm powers for relatively small input powers [see Fig. 4(d)], making this an interesting system for future study.

While we have described some of the interplay between laser intensities, Rb density, and laser frequency detunings for the generated 420 nm and 1324 nm coherent beams, a theory is yet to be developed which provides an upper limit on the efficiency of these multiple wave mixing processes. Further insight can also likely be gained by examining isotopically pure Rb vapor cells which greatly adjusts the ground state hyperfine splitting, and by using vapor cells which allow the observation of the 5.23 μm and 2.73 μm beams so they can also be studied.

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